

ELECTROSTATIC DISCHARGE EFFECTS ON THIN FILM RESISTORS

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ABSTRACT

Recently, open circuit failures of individual elements in thin film resistor networks have been attributed to electrostatic discharge (ESD) effects. This paper will discuss the investigation that came to this conclusion and subsequent experimentation intended to characterize design factors that affect the sensitivity of resistor elements to ESD. The ESD testing was performed using the standard human body model simulation.

Some of the design elements to be evaluated were: trace width, trace length (and thus width to length ratio), specific resistivity of the trace (ohms per square) and resistance value. However, once the experiments were in progress, it was realized that the ESD sensitivity of most of the complex patterns under evaluation was determined by other design and process factors such as trace shape and termination pad spacing.

This paper includes pictorial examples of representative ESD failure sites, and provides some options for designing thin film resistors that are ESD resistant. The risks of ESD damage are assessed and handling precautions suggested.

BACKGROUND

This investigation into the sensitivity of thin film resistors to damage from Electrostatic Discharges (ESD) began as a result of a failure investigation. A hybrid electronic module for the Hubble Space Telescope gyro assembly failed during ground-level testing. The cause of the failure was isolated to a thin film resistor chip, which had developed an open circuit. Visual examination of this resistor showed damage in the form of apparent cracks in the resistive film, in this case nichrome. These "cracks" were parallel to the minor axis of the resistor and crowded together in areas where the trace width was a minimum. At first it was suspected that this damage resulted

from some kind of over-power condition experienced during testing. Attempts to simulate this damage on spare resistor chips were unsuccessful, using both constant power and pulse power levels relevant to the application. Even excessively high power levels were unable to duplicate the observed effects. Testing using equipment designed to test for ESD sensitivity, however, produced the same kind of transverse, jagged, roughly parallel cracks as in the failed resistor. We concluded that we had experienced an ESD event on the Hubble hybrid. This was an unusual occurrence, so we decided to investigate further, to determine what our risk of further instances of this kind was likely to be.

THE EXPERIMENTAL CONCEPT

We chose to use thin film resistor networks as our experimental subjects for a variety of reasons. We had a significant number of resistor networks in a variety of configurations (see Figure 1) available to us from our stock of flight spares. Most had been packaged in Dual In-line Packages (DIPs), which were easily accommodated by our ESD tester. In addition, it was useful for our study that all resistors on a single substrate would be made with the same film thickness and composition, regardless of resistance value. We also believe that most of the current thin film resistor chip usage by NASA is in the form of networks. In addition to the packaged networks, we were able to acquire eleven different patterns of "block" style resistors made with both nichrome and tantalum nitride films, from the manufacturer of the Hubble hybrid. These were subsequently packaged into 28 pin DIP packages for use in our study.

We initially set out to measure the physical dimensions of the resistor elements and to attempt to relate these dimensions to ESD sensitivity. In fact, we soon found that the simple effects of dimensional variation were overshadowed by the effects of configuration features in the resistor traces, particularly serpentines and laser trims. Serpentine configurations are commonly used to

generate the maximum resistance in the minimum area while minimizing inductance and meeting power-handling requirements. Laser trimming is used to adjust the resistance value of an untrimmed block to the value desired by the customer. Laser trimming allows one basic resistor pattern to be used for an extensive range of final resistance values. Typically, laser trimming either reduces the effective line width for a portion of the resistor trace, or increases the path length traversed by the current through the resistor.

We used a commercial ESD tester, the System 700 made by Oryx Technology/IMCS Division to perform the ESD characterizations. This equipment is designed to test per the Human Body Model (HBM), which simulates a pulse from a person (100pF) discharging through skin (1500 ohms). The equipment was set-up and used in accordance with the manufacturer's instructions and the general operating requirements of MIL-STD-883E Method 3015.7. Our test conditions often varied from strict compliance with Method 3015.7, to better investigate the phenomena we were observing.

A published listing of the ESD sensitivity of various electronic parts¹, shows resistors as sensitive in the voltage range of 500-3000, or Classes 1 and 2 (Table 1) of MIL-STD-883E Method 3015.7². This source also provides a table of typical ESD voltages generated under various environments (Table 2). It can be seen that common events can produce voltages high enough to damage film resistors, so why is ESD damage of resistors apparently so rare? It may be because typical resistor package geometries are difficult to discharge into or that they readily dissipate charge, or because the effects of ESD may be subtle and go unnoticed. We attempted to explore these possibilities in our investigations.

Table 1. ESD Sensitivity Classes

Class 1	0 volt to 1,999 volts
Class 2	2,000 volts to 3,999 volts
Class 3	4,000 volts and above

Due to the limited quantity of samples of each network type (in some cases only one sample was available), it was necessary to perform consecutive ESD pulses on most of the resistive elements. It is understood that this imposed a certain degree of error due to cumulative damage, but this was

unavoidable. Because of the sometimes subtle variations in the pattern shape or width it was impossible to accurately estimate the effect of cumulative damage on the resistance measurements. When possible, however, an additional sample of a resistive path was given a single pulse at a voltage well above the damage threshold, and the resistance was measured. Usually these measurements fell either within the distribution for the sequential measurements or only slightly lower, so it is believed that the cumulative damage effect was not major.

THE PARTS

The test resistors were primarily thin film resistor networks made by one manufacturer but to different specifications and with a large spread of lot date codes. In addition, we had discrete chips made with both nichrome and tantalum nitride films that were supplied by the Hubble hybrid manufacturer. The latter were mounted for convenience in DIP packages and wire bonded to make connections so as to be as similar to the other test subjects as possible. We did not put the lids on the packages we assembled and we removed the lids from the flight stock parts. This was to make examination easy at any point during the execution of the ESD test. Table 3 summarizes the characteristics of the resistor networks that were tested.

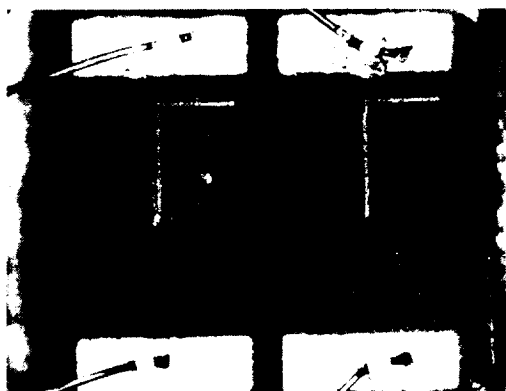
TEST METHODS

Testing was not performed in strict accordance with MIL-STD-883E Method 3015.7; rather the test method was modified in reaction to observed behaviors. In some cases, a single pulse at each of a series of increasing voltages was used. In other cases, a succession of pulses at a single voltage was used. Where sufficient quantity of the same resistor network was available, one part was usually sacrificed in order to gain insight into the behavior of that particular configuration. Once the general behavior was understood, a relevant test approach was selected for that specific part type.

In the beginning, the process consisted of measuring the initial resistance of the sample, subjecting the sample to the ESD insult, then remeasuring the resistance value and either increasing the voltage or applying another pulse at the same voltage. This process was typically continued until the resistance value had increased to twice the initial value. However, the results from this simple approach were soon seen to contain unexpected or anomalous behaviors. Graphs showing examples of resistance change

Table 2. ESD Voltage Levels Generated by Common Activities

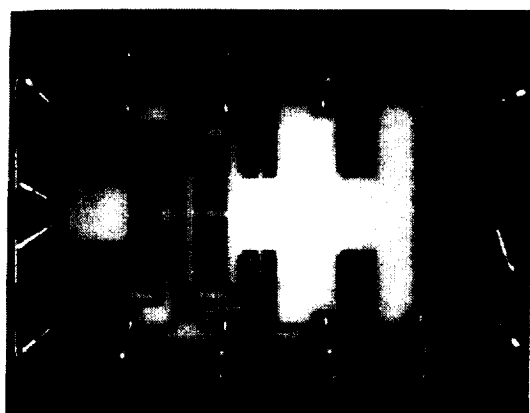
Means of Generation	10 - 25% Relative Humidity	65 - 90% Relative Humidity
Walking across carpet	35,000 volts	1,500 volts
Walking across vinyl tile	12,000 volts	250 volts
Worker at bench	6,000 volts	100 volts
Poly bag picked up from bench	20,000 volts	1,200 volts
Chair with urethane foam	18,000 volts	1,500 volts



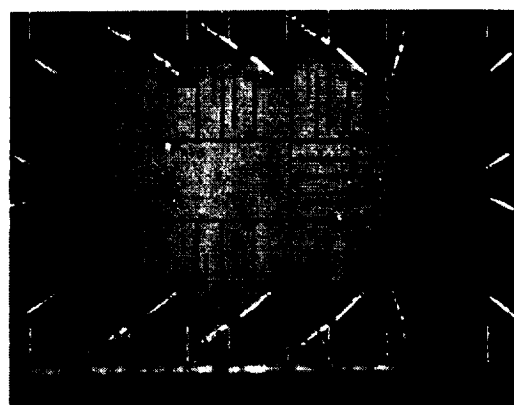
a) TF - Simple Block



b) ND - Serpentine Block



c) NP - Very Complex Serpentine



d) NO - Similar to NP but with floating blocks

Figure 1. Examples of Pattern Types Tested

Note: Pattern NO is more susceptible to internal arcs than Pattern NP because of the presence of floating blocks. However, these internal arcs provide some protection to the pattern, and NO is less ESD sensitive than NP.

characteristics are shown in Figures 2 through 5. The resistor samples were then examined under a microscope in order to see if there were differences in the damage characteristics for resistor elements exhibiting the various behaviors. These observations proved very informative. It was found that an inspection technique called "vicinal illumination"³ was most useful in observing the ESD-induced damage.

Vicinal Illumination

Vicinal illumination is a microscopy technique whereby a translucent material is illuminated in a small concentrated area, so as to illuminate the material from within as a result of light scattering. The result is a low intensity, diffuse illumination that clearly reveals any gaps in an opaque layer covering a translucent substrate such as a resistor trace on an alumina substrate. Vicinal illumination revealed damage to the resistor trace that was essentially invisible when viewed using reflected incident light and often obscured by glare when using side lighting. Under vicinal illumination it was possible to follow the full extent of the damage, no matter how complex the pattern.

Vicinal illumination is easily achieved using a standard metallurgical microscope with incident lighting. The light source output should be maximized by opening the aperture diaphragm completely and removing all filters from the optical path. The field diaphragm is then closed completely, resulting in a small spot of light on the sample surface. Images showing ESD damage to resistors were generally recorded using a CCD camera and video printing system, but the image through the eyepieces was typically much higher quality due to the low level of the scattered light. Care should be taken to avoid locating this spot on a reflective surface (such as a nichrome resistive trace) to prevent eye discomfort from the intensely bright reflection. While this technique can be performed using objectives between 5 and 50 times magnification, the most successful observations were accomplished using a 20 times objective. Particularly on microscopes in which the field diaphragm does not close very tight, it is useful to perform inspections at higher magnification so that the light spot introduced is smaller.

Visual Monitoring

Some of the resistors seemed to be remarkably free of damage, and others were damaged in unexpected ways, so another microscope was positioned over the device being tested to see if

there was any arcing visible and if so, where it was occurring. A stereo microscope mounted to a long boom was used at 45X magnification with no external lighting. Photographs of arcs, such as Figure 10, were achieved using a simple view camera, open shutter photography, and fast film. The combination of human monitoring and photography enabled the path of the arc to be determined.

Scanning Electron Microscope

A Scanning Electron Microscope (SEM) was used to examine some of the more interesting or puzzling examples of damage in greater detail. The SEM was used to look for changes in grain structure, signs of melting or fusing, and to explore the extent of any cracks that might be present. Unfortunately, SEM inspections to date have been inconclusive. SEM inspection of tantalum nitride resistors has been much more successful than of nichrome resistors as shown by Figure 11.

TEST RESULTS FOR NICHROME RESISTORS

The slope of the resistance versus imposed ESD voltage curve indicated four basic effects: little or no damage, current crowding, internal arcing, and external arcing. It should be noted that most of the resistive traces exhibited some, but rarely all, of these effects. For example, one sample of style NN exhibited only the "no effect" and "external arcing" effects due to the close spacing of the substrate bond pads. In another example, several traces in another network experienced no damage until 3000 volts, then exhibited external arcing at all voltages over 4000 volts (after the initial damage, however, the damage threshold decreased significantly).

"Little or no effect" region: Some resistors were visually inspected after each ESD pulse in order to establish a damage threshold, below which no damage (typically corner cracking) was visible at 200X using vicinal illumination. The typical resistance change (ΔR) threshold range for visible damage was 0.2 to 1.3 percent. Above this general range the effects of current crowding were usually observed. The smallest values measured for ΔR were 0.01 percent.

"Current crowding" region: The damage associated with the lowest voltage (and therefore lowest energy) pulses above the damage threshold involved the appearance of "cracks" in the resistive trace at corners and the tips of laser trims. These features resembled the branches of trees in that

Table 3. Summary of Test Sample Resistor Patterns and Test Results

Pattern Code	Element Material	Pattern Type	Resistance Values (Ω)	ESD Sensitivity	Observations
ND	Nichrome	Block - Serpentine	1000	Sensitive at Class 1 but capable of surviving many zaps at 15.5kV. Linear ΔR for each repeated zap at 1000V of +0.09% and at 15.5kV of +0.62%/zap	Arcs at laser tips and adjacent bond pads
NG	Nichrome	Block - Serpentine Polymer Coated	2000	Sensitive at Class 1.	Internal arc and surface track on polymer
			10000	Insensitive up to maximum volts	Surface track on polymer
			25000	Insensitive up to maximum volts	External arc
NH and NI	Nichrome	Serpentine - Complex	1250	Class 2	Current crowding and internal arcs
			2500	Class 2	Current crowding and internal arcs
			10000	Class 3	Arcs across serpentine turns
			25000	Class 2	Internal arcing only
NM	Nichrome	Block - Simple Packaged by GSFC	300	Class 2	Laser trim current crowding then arcing from laser kerf to bond pad Also arced to wire around resistor
NN	Nichrome	Serpentine - Moderate Polymer Coated	All except 10000 ohm	Abrupt, dramatic resistance increase at sensitive voltage. Resistor tends to open circuit	Wider cracks than typical NiCr Polymer damaged and discolored
			1250	Class 1	Arced to avoid trace Heavy damage to polymer
			2500	Class 2	Localized current crowding
			5000	Class 2	Localized current crowding
			10000	Insensitive up to maximum volts	No damage whatsoever
NO	Nichrome	Serpentine - Moderate	2500	Class 1 / 2	Arced across serpentine turns and laser kerfs
			5000	Class 3. Essentially no effect up to 15.5kV	External arc between bond pads
			10000	Class 3. Repeated zaps at 15.5kV caused significant increase in resistance: 90% after 8 zaps	Internal arc to floating trace and back into resistor to form a straight line
				Class 1	Current crowding and internal arcs
NP	Nichrome	Serpentine - Very Complex	625	Class 1	Current crowding and internal arcs
			5000	Class 2	Current crowding and internal arcs
			9400	Class 2	Internal arcing between pads
TB	Tantalum Nitride	Block - Serpentine Packaged by GSFC	195	Class 1. Resistance decreases initially by about 0.2% but increases suddenly above 2 kV to over 3% at 3kV	Current crowding at all laser trim tips and some internal arcing over laser kerfs
TF	Tantalum Nitride	Block - Simple Packaged by GSFC	145	Class 1. Resistance decreases ~ 0.6% to 3kV when it begins to increase to ~ 5% at 10kV. Repeated zaps at 1500 volt produced a decrease of 1.2% after one zap and no more change for the next nine zaps	Current crowding at all laser trim tips and some internal arcing from bond pad to laser kerf
TG	Tantalum Nitride	Block - Simple Packaged by GSFC	100	Class 1. Resistance decreases by ~ 0.2% to 4kV when it begins to increase to ~21% at 15.5kV.	Current crowding at all laser trim tips and some internal arcing over laser kerfs

they split off into numerous smaller paths as they develop at higher voltages. It is believed that these features are not actually cracks in the truest sense of the term because they are most likely thermally generated and not strictly mechanical in nature, but the term "crack" best describes their appearance. Vicinal illumination confirms that the opaque resistive material is missing within these crack features. Their appearance and location suggest that the cracks are a result of higher current density around corners in the resistive trace (current crowding). Hagedorn and Hall⁴ have shown that the maximum current density in a right angle turn with a radius of 1% of the trace width (a relatively sharp bend) is more than six times the current density in the straight portion of the resistive trace. In some cases the cracks were observed across the entire width of the resistive trace, but often the growth of the cracks was suspended by the transition to internal or external arcing, which shunted the current, preventing it from flowing through the portions of the resistor which exhibited corner cracking. This transition was heavily influenced by the increase in resistance associated with the corner cracking mechanism.

"Internal arcing" region: As the voltage (and therefore the energy) of each ESD pulse was increased, eventually arcing would occur within the resistive pattern. The location of such arcs varied from the base of the laser trim to gaps created by the serpentine pattern to high potential difference gaps created when the pattern "doubled back" on itself. The arcs tended to occur in as straight a line as possible between the substrate bond pads. In addition to the resistance change evidence, vicinal illumination revealed a distinctive appearance for the damage resulting from internal arcing. The lower potential side of an arc always exhibited a branched crack structure extending into the trace from an edge, and the high potential side exhibited only a few small chunks of nichrome missing from the edge of the trace. During somewhat higher voltage ESD pulses the arcs were observed directly using a stereo microscope. Several of these arcs were photographed (see Figure 11), recording the locations of the arcs. Internal arcing was often accompanied by the transverse cracks first observed in the Hubble failure. It is believed that these cracks were the result of increased current density along thin areas of the nichrome, exacerbated by the low effective resistance experienced by the arc, producing higher current flow. At higher ESD voltages external arcing tended to predominate.

"External arcing" region: Many, but not all, resistor networks exhibited some degree of arcing outside the resistive trace. The potential locations

of these arcs were between package bond pads, from package bond pads to substrate bond pads, between substrate bond pads, between adjacent resistors, and even between the bond pads and adjacent bond wires. External arcing usually shunted all of the current flow through the resistive element, but in some cases the resistance continued to change despite external arcing, indicating that some amount of current flow was causing damage to the remaining resistive material. External arcing was typically easy to observe using the stereo microscope described above, and it was observed that the location often shifted slightly from one ESD pulse to the next. Visual inspection at higher magnification revealed that external arcing typically resulted in metal deposition near the low potential side of the arc, and a melted appearance on the surface of the high potential side of the arc.

TEST RESULTS FOR TANTALUM NITRIDE RESISTORS

The tantalum nitride resistors tested to date have been simple block designs with "L-cut" laser trims. During the incremental voltage tests the voltage was ramped from 100 to 15,500 volts in steps ranging from 100 to 1000 volts. In all cases the resistance decreased after each pulse until approximately 3500 volts, then increased rapidly. The maximum ΔR 's measured were approximately 3.8 percent negative and 25 percent positive. One group of resistors was tested at opposite polarity, with close correlation of the parts within each test condition. Those tested with the high potential connected nearest the laser trim experienced larger resistance shifts (both positive and negative) than the resistors tested with the low potential near the laser trim. It is unclear what importance this may have, and further investigation is planned. Additional testing on tantalum nitride resistors in general is planned for the next phase of our study.

DISCUSSION

The presence of a direct ground connection at one end of the resistor was required in all cases to produce ESD damage. Several resistors were tested without any ground connection to the subject resistor or an adjacent trace, and in no case was any damage observed, either electrically or visually. This finding was confirmed by Chase⁵ and is significant, since it helps to explain why ESD failures are not more common in thin film resistors. Consider the case of a discrete packaged resistor network. Damage to any individual resistor in it would be extremely unlikely given that an ESD pulse would need to be delivered while the pin connected to the other end of the resistor (typically

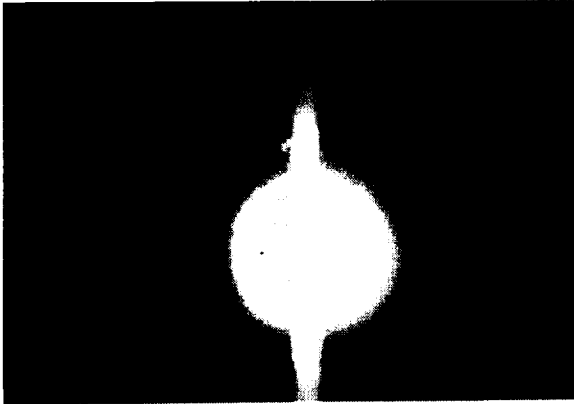


Figure 6. Vicinal illumination photograph showing an internal arc across the laser kerf.

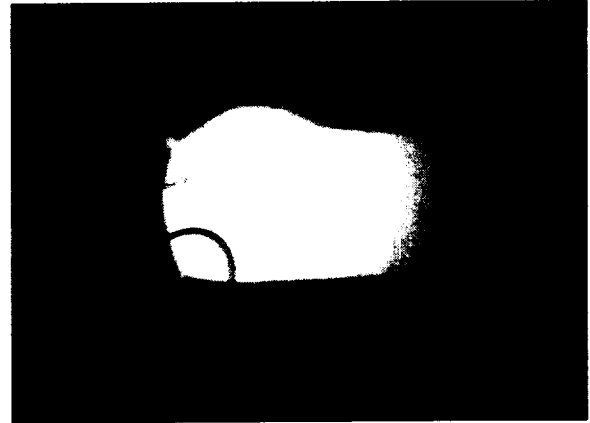


Figure 7. Vicinal illumination photograph showing ESD damage to a typical serpentine turn.

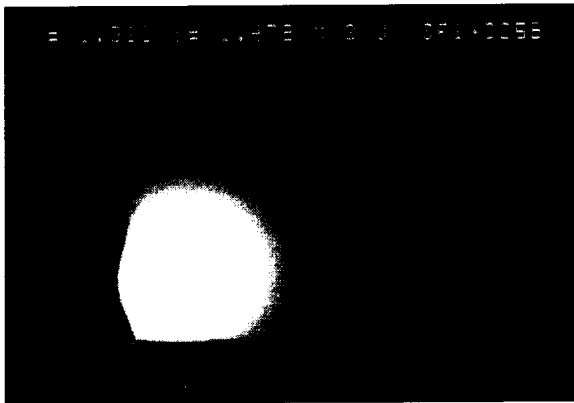


Figure 8. Vicinal illumination photograph showing typical corner cracking in a polymer coated resistor network.

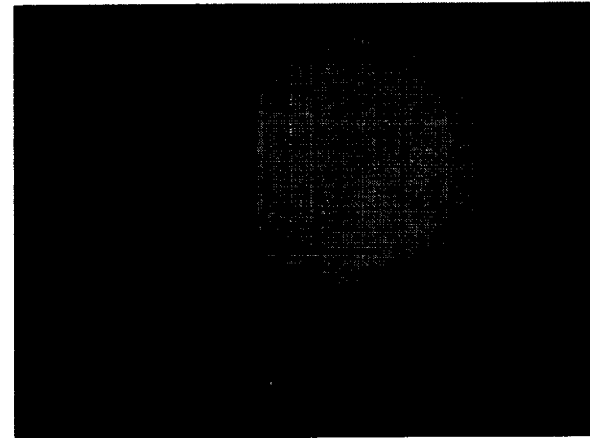


Figure 9. Vicinal illumination photograph showing typical parallel transverse cracking associated with internal arcing.

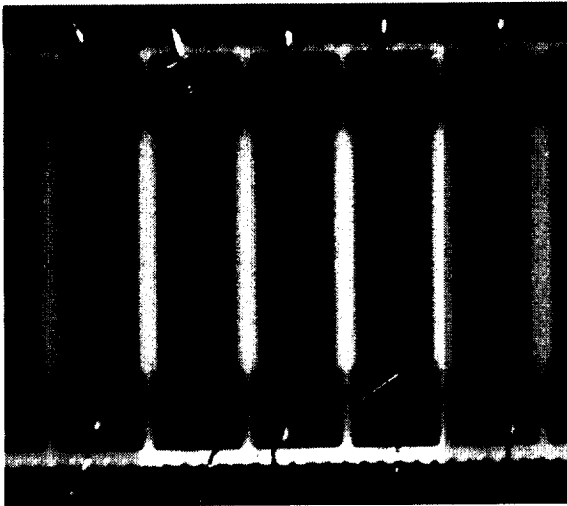


Figure 10. Open shutter photograph showing the internal arc location on a typical ND resistor.

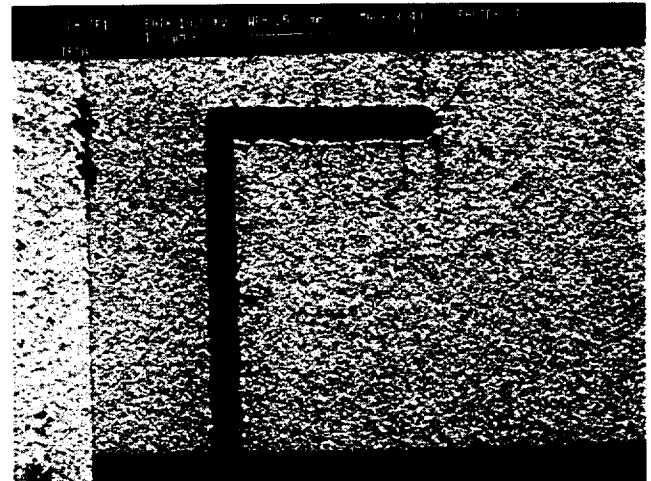


Figure 11. SEM photograph showing "cracking" at the tip of the laser kerf and internal arcing damage between the bond pad and laser kerf.

an adjacent lead) was connected to ground potential. This need for a ground suggests that thin film resistors are much more susceptible to ESD damage after being installed into larger assemblies that have their own ground connection. This was the precise situation for the Hubble failure, which was mounted in a hybrid, and was found during board level testing.

One concern raised by our work is the existence of latent damage in most of the resistors we tested. There is a general awareness in the industry of the static sensitivity of active parts, but passives are often assumed to be impervious to ESD damage. Because we have shown that a resistor can be partially damaged without resulting in an open circuit, damage caused by ESD may not be detected in the circuit. It is not presently known what effect ESD damage may have on the long-term reliability of a resistor. It is certainly conceivable that the increased current density caused by corner crowding may cause premature failure under operating conditions.

Several techniques for static discharge protection have been proposed. One suggestion is the use of rounded corners in serpentine traces and arches in ladder adjustment patterns⁶. The same source also recommends gold coating corners wherever possible. Our work indicates that location of laser trim kerfs as far away from the end connections as possible discourages internal arcing, which was typically the largest source of resistance shift. This, unfortunately, directly conflicts with the advice of another paper⁷ to locate the laser trim kerfs close to the end connections for improved temperature stability.

The presence of a polymer coating (assumed to be polyimide) on two of our test samples produced some interesting results. At low ESD voltage the polymer apparently acted as an insulation blanket, preventing heat flow out of the resistor trace especially in corners. As a result these samples exhibited much heavier localized damage, wider cracks in the nichrome traces, and the very predictable response shown in Figure 3. At higher voltages, the coating apparently produced a carbon surface track during arcing events. The development of this stable arcing path protected the resistor from further degradation during repeated high voltage ESD events.

A few resistors were exposed to repeated ESD pulses at the same voltage, with resistance measurements between all pulses. Plots of this data (see Figure 2) show that the resistance increase is basically linear, with a slope

proportional to the imposed ESD voltage. Extended pulses eventually resulted in catastrophic failure. Visual inspections between each pulse show that the corner cracks grew steadily until the resistance of a serpentine trace had increased sufficiently to encourage internal arcing across the serpentine gap. The effects of current crowding and transition to internal arcs were discussed previously. Subsequent pulses produced continued arcing, eventually resulting in an open circuit and usually transverse cracks similar to the Hubble failure.

It is our strong suspicion that ESD damage represents an increasing threat to thin film resistors, particularly thin film networks, as physical sizes are reduced and patterns become more complex.

FUTURE WORK

As is so often the case, our investigation seems to have asked more questions than it has provided answers for. The surprising result that Tantalum Nitride resistors can show negative changes in reaction to ESD needs to be investigated. Is this behavior dependent on the manufacturer's processing? Does it happen with serpentine as well as block patterns? We plan to procure both block and serpentine pattern Tantalum Nitride resistors from a different manufacturer in addition to performing further testing on the present samples.

We have experimented briefly with changes in polarity on Tantalum Nitride samples and have observed some interesting effects that need to be investigated further. This testing is also needed for nichrome, to see if the previously noted difference between the two systems extends to polarity sensitivity as well.

We postulated from our work that rounding the inside of serpentine bends would reduce current density and thus increase robustness but we did not test this hypothesis. We have samples with radiused bends that will be tested in the next phase of our work.

A major concern of exposure to ESD, is that the resultant damage may not cause an unacceptable change in key parameters immediately, but might shorten resistor life. We intend to investigate this risk by performing life test on parts known to exhibit corner cracks, transverse cracks, flashover trees, or other manifestations of ESD damage.

We have been fascinated by the crack-like damage areas in both nichrome and tantalum resistors. SEM examination revealed that the "cracks" are quite wide and deep suggesting that material has been expelled. Has resistor film material been evaporated? If so, this would make the theoretical analyses by several previous authors inaccurate because they based their approach on the temperature required to melt, not evaporate the film^{8,9,10,11,12}. We will attempt to capture and analyze any material that is emitted, and use this information to develop an improved model of ESD damage.

CONCLUSIONS

1. Thin film resistors made from both Tantalum Nitride and Nichrome are ESD sensitive. Depending upon a large number of factors, sensitivity may be at the MIL-STD-883E Method 3015.7 Class 1,2 or 3.
2. The level of sensitivity of the resistor patterns tested in this investigation was influenced by many unexpected factors in addition to or instead of simply the width, length, thickness and resistivity of the resistance trace.
3. Some of these factors, such as the spacing of the pads at each end of a resistor trace can be exploited as design features to provide ESD protection.
4. However, too close spacing of the pads of separate resistors can lead to unexpected damage, caused by the ESD pulse jumping to the adjacent resistor.
5. ESD damage to nichrome based resistors can be expected to produce an increase in resistance, whereas tantalum nitride base resistors may decrease in resistance when subjected to pulses in the Class 1 and 2 range.
6. The characteristics of the damage are fairly predictable depending on the form of the resistor trace, serpentine patterns tend to show damage on the inside radius of the bends, laser scribes show arc damage, etc.
7. The dimensions and location of laser trims can significantly impact the ESD sensitivity of thin film resistors.
8. Some of the ESD damage characteristics are asymmetrical in respect to the polarity of the applied charge.
9. The location and shape of the damaged areas can be used to estimate the magnitude and polarity of the ESD insult.
10. In practice, ESD damage to thin film resistors is probably quite rare due to the need for the simultaneous combination of a charged surface and a grounded surface coming in contact with the opposite ends of a resistor trace.

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REFERENCES

- 1 "The Basics of Electrostatic Discharge", The ESD Association, <http://www.borg.com/eosesd/cebasics.html> (1996)
- 2 MIL-STD-883E, Method 3015.7, "Electrostatic Discharge Sensitivity Classification", (1989)
- 3 S. Hull, "Detection of Cracks in Ceramics Used in Electronic Devices Using Light Scattering", Nondestructive Characterization of Materials VI, p. 469, Plenum Press, NY (1994)
- 4 F.B. Hagedorn and P.M. Hall, "Right Angle Bends in Thin Film Strip Conductors", Journal of Applied Physics, Vol. 34, No. 1, pp. 128-133 (1963)
- 5 E.W. Chase, "Electrostatic Discharge (ESD) Damage Susceptibility of Thin Film Resistors and Capacitors", EOS/ESD Proceedings, pp.13-18 (1982)
- 6 T.T. Lai, "Electrostatic Discharge (ESD) Sensitivity of Thin-film Hybrid Passive Components", Proceedings 39th Electronic Components Conference, IEEE, pp. 229-239 (1989)
- 7 J. Ramirez-Angulo, R. Wang, and R. Geiger, "Improvement of Laser Trimmed Film Resistor Stability by Selection of Optimal Trim Paths", IEEE International Symposium on Circuits and Systems, pp. 2188-2191 (1991)
- 8 T. T. Lai, "Electrostatic Discharge (ESD) Sensitivity of Thin-film Hybrid Passive Components", IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. 12, Issue 4, pp. 627-638 (1989)
- 9 A. J. Wallash, "Electrostatic Modeling and ESD Damage of Magnetoresistive Sensors", IEEE Transactions on Magnetics, Vol. 32, Issue 1, pp. 49-53 (1996)
- 10 A.J. Wallash, T. S. Hughbanks, and S. H. Voldman, "ESD Failure Mechanisms of Inductive and Magnetoresistive Recording Heads", EOS/ESD Proceedings, pp. 322-330 (1995)
- 11 J. Smith and W. Littau, "Prediction of Thin-film Resistor Burnout", EOS/ESD Proceedings, pp. 192-197 (1981)
- 12 R. A. Launer, J. T. May, L. M. Richard, "Interpretation of EOS Damage in NiCr Resistors", Proceedings of ISTFA, pp. 279-284 (1990)